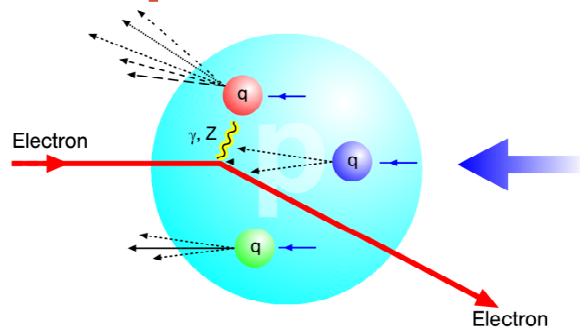


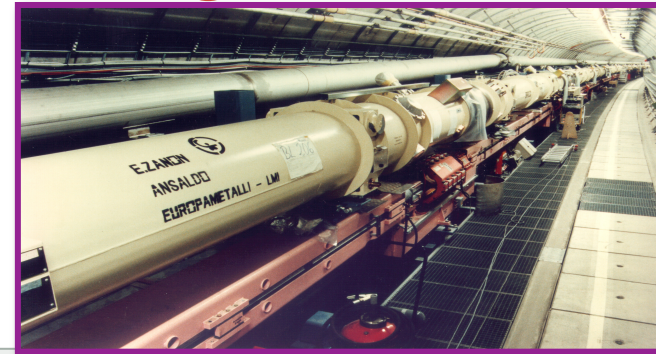
ERL-BASED ELECTRON-ION COLLIDERS

Vadim Ptitsyn
Collider-Accelerator Department
BNL

Lepton-nucleon scattering



- **Deep Inelastic Scattering (DIS)** of electron, muon and neutrino beams on nucleons (fixed targets) has been a vital scientific exploration tool for several decades.
- Experiments at SLAC (late 60s) led to the quark-parton model of nucleons, and ultimately to establishing QCD theory.
- Numerous DIS experiments in 70-80s uncovered the momentum and spin distribution of quark constituents of proton and neutron



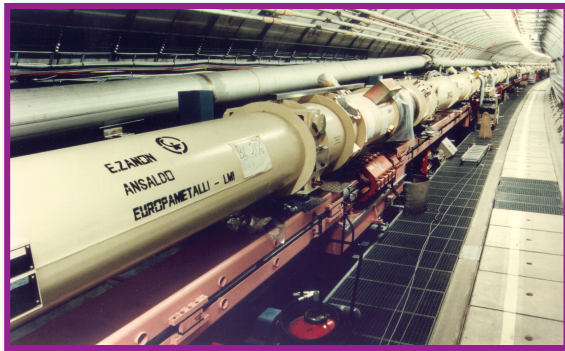
HERA (1991-2007): first electron-proton collider
Higher CME \rightarrow reach to the momentum distribution of quark and gluons at very low momentum fraction (x)

Selection of physics results:

- **precise data on details of the proton structure**
- **the discovery of very high density of sea quarks and gluons present in the proton at low- x**
- **detailed data on electro-weak electron-quark interactions**
- **precision tests of QCD (α_s measurements)**

From HERA to future colliders

HERA

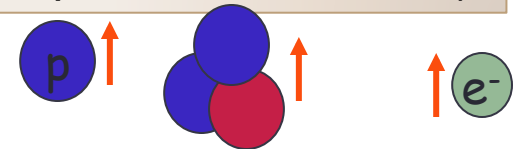


Polarized e^-, e^+ (27.5 GeV)
Unpolarized protons (920 GeV)
Peak luminosity: $5 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

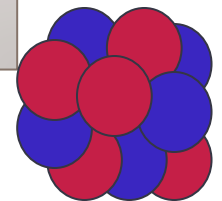
Future colliders

Much higher luminosity:
 $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Polarized protons and light ions
(in addition to polarized electrons)

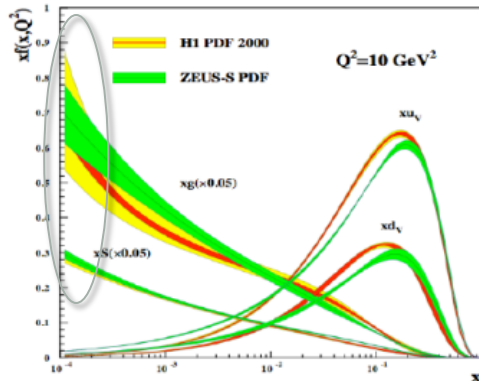


Heavy ion beams



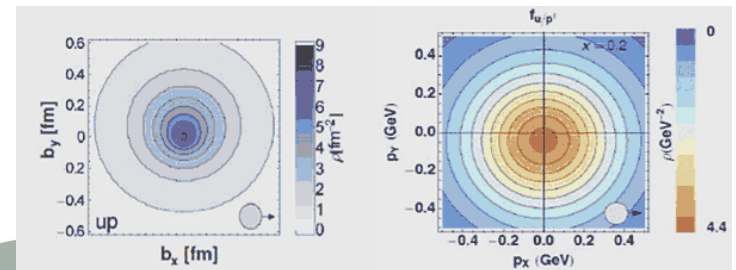
Different (and variable)
Center-of-Mass Energy
range

Major physics objectives of future electron-ion colliders



Mapping the gluon content of ions and protons;
High-density gluon state

3-dimensional imaging of the nucleons

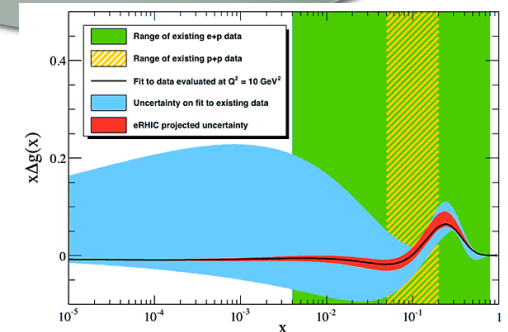


Spatial and Momentum Structure of the Nucleus

Electron-ion colliders

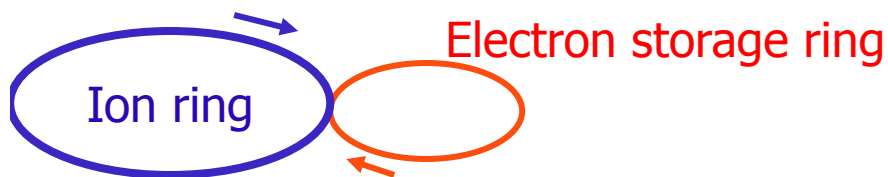
Probing the nucleon's spin structure

Searches and the understanding of new physics
(GUT, LQs, Higgs,)



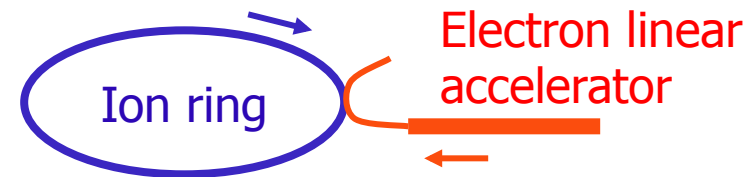
Electron-Hadron Collider Designs

Ring-ring



	Center of Mass Energy	On the base of
LHeC ring-ring	1.3 TeV	LHC (CERN)
MEIC	15-65 (140) GeV	CEBAF (JLab)
e-HIAF	12 GeV	HIAF (IMP)

Linac-ring ERL-based



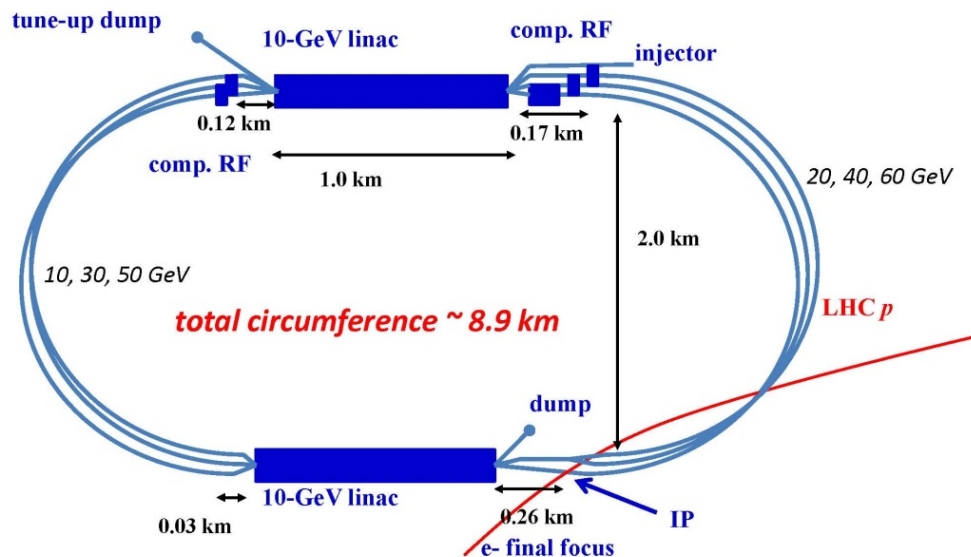
	Center of Mass Energy	On the base of
LHeC linac-ring	1.3 (2) TeV	LHC (CERN)
eRHIC	20-145 GeV	RHIC (BNL)

-Overcoming the electron beam-beam limit
 -Spin transparency
 Energy Recovery Linacs have to be used for high luminosity in CW mode



Large Hadron electron Collider at CERN

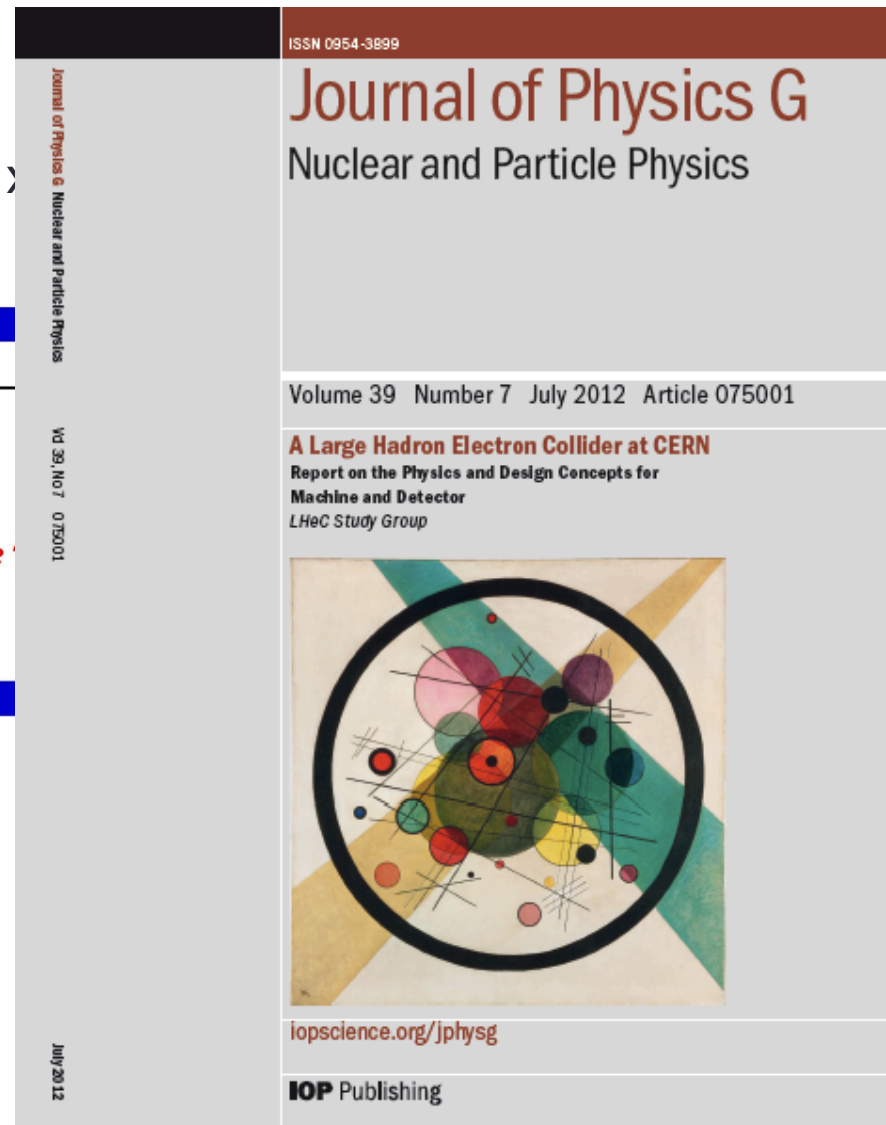
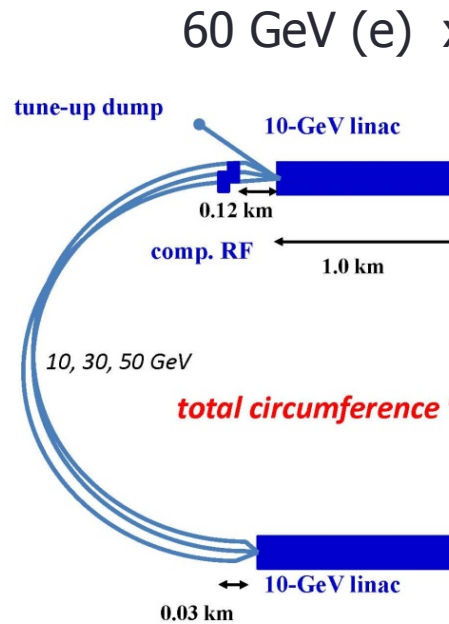
60 GeV (e) x 7 TeV (p)



- Protons/ions from LHC
- 0.5 GeV injector
- A pair of SCRF linacs with energy gain 10 GeV per pass
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations to compensate energy lost by SR
- Switching stations at the beginning and end of each linac
- Matching optics
- Extraction dump at 0.5 GeV



Large Hadron electron Collider at



ns from LHC

jector

CRF linacs with energy
eV per pass

rcs, each arc 1 km radius

erating stations to
te energy lost by SR

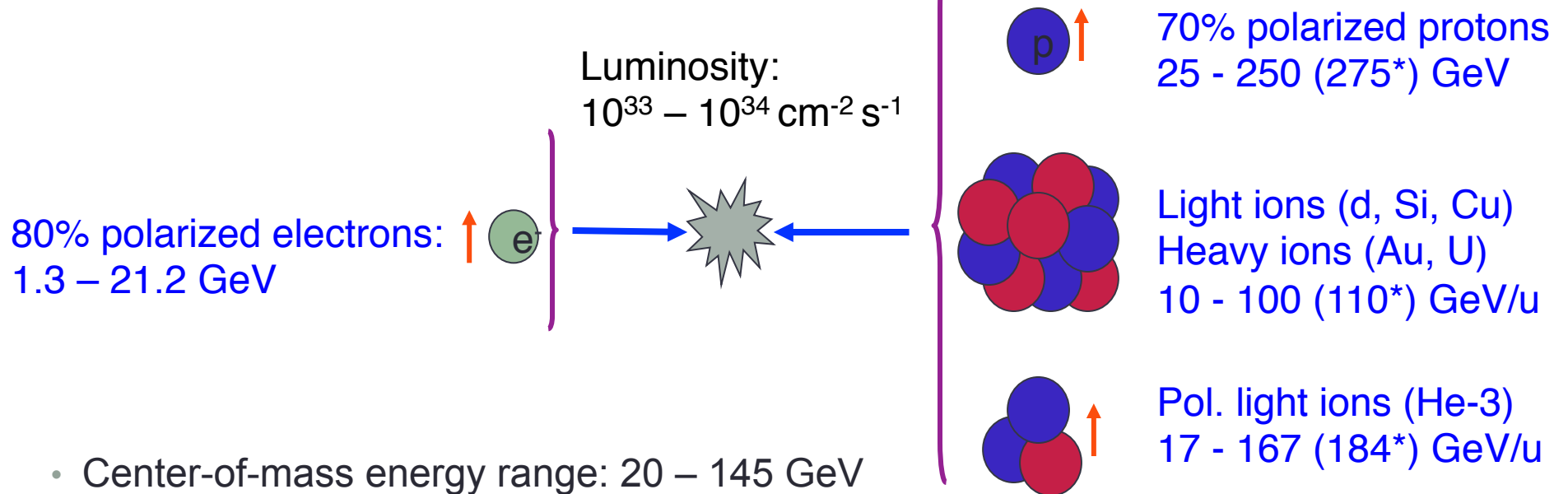
stations at the beginning
each linac

optics

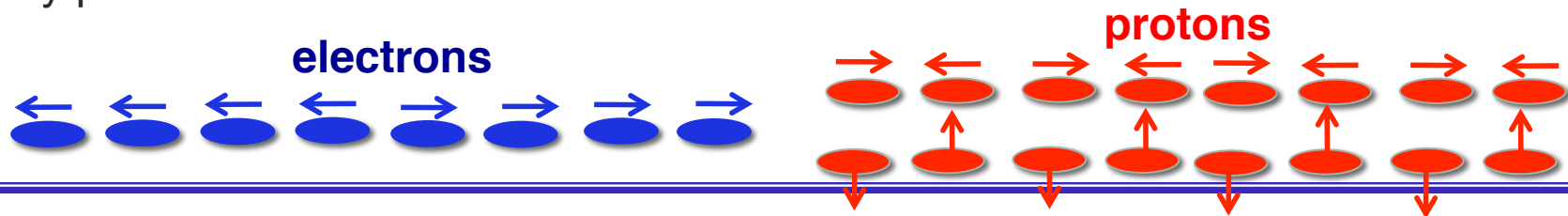
dump at 0.5 GeV

eRHIC at BNL

Add an electron accelerator to the existing \$2.5B RHIC including existing RHIC tunnel, detector buildings and cryo facility



- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



* It is possible to increase RHIC ring energy by 10%

ERL-based eRHIC

FFAG Recirculating Electron Rings

1.3-5.3 GeV

6.6-21.2 GeV

ERL Cryomodules

Beam Dump

Energy Recovery Linac,
1.32 GeV

Polarized
Electron Source

Coherent
Electron Cooler

Detector I

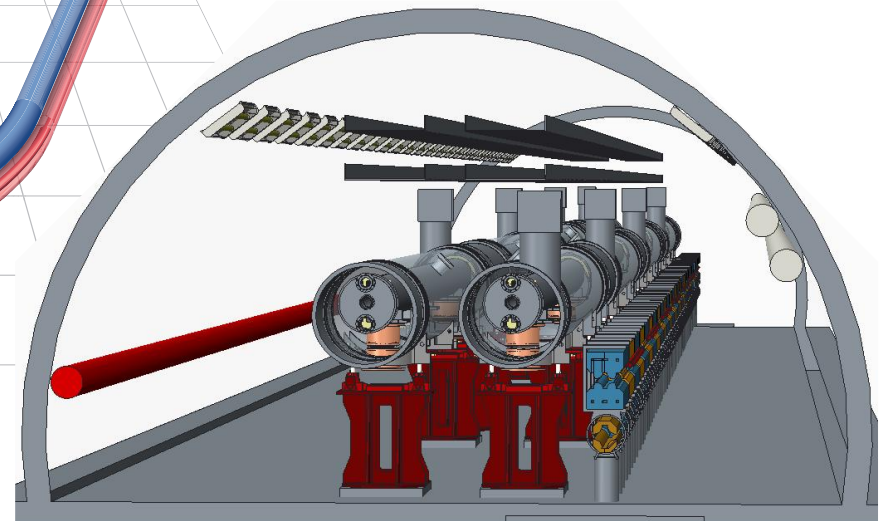
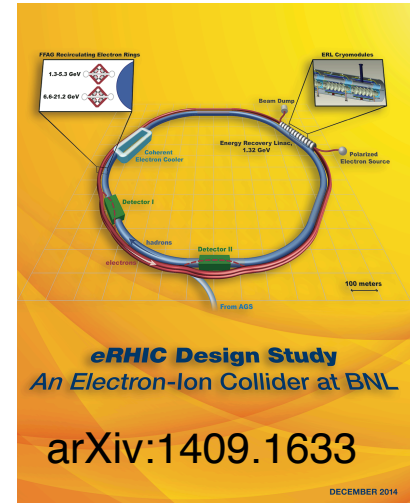
hadrons

Detector II

electrons

From AGS

Novel FFAG lattice allows 16 beam re-circulations using only two beam transport loops

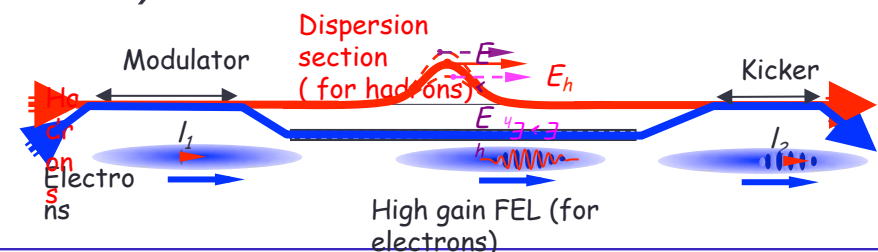
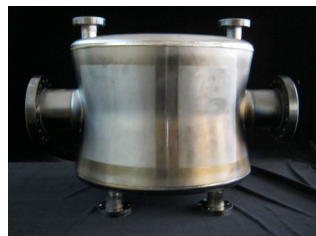
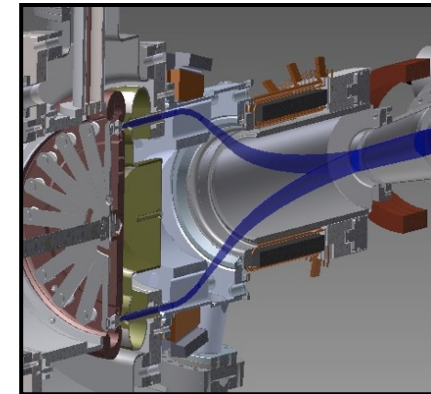


Parameter Table

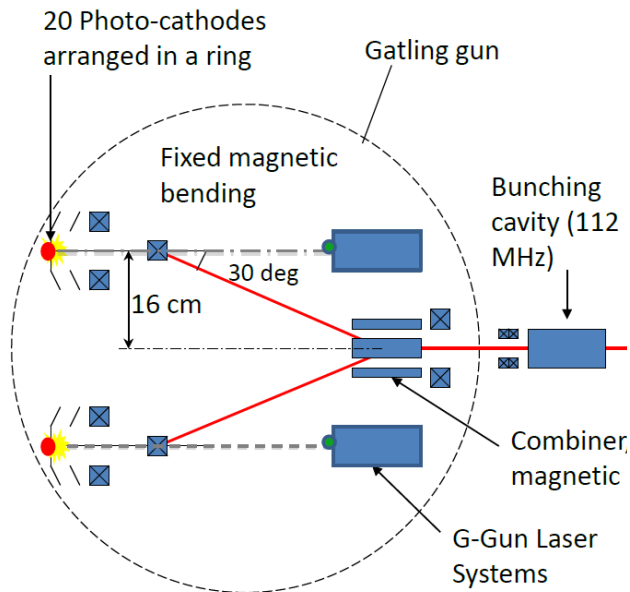
Parameters	eRHIC		LHeC	
	e	p	e	p
Energy (GeV)	15.9	250	60	7000
Bunch spacing (ns)	106		25	
Intensity, 10^{11}	0.07	3.0	0.01	1.7
Current (mA)	10	415	6.4	860
rms norm. emit. (mm-mrad)	23	0.2	50	3.75
$\beta_{x/y}^*$ (cm)	5	5	12	10
rms bunch length (cm)	0.4	5	0.06	7.6
IP rms spot size (μ m)	6.1		7.2	
Beam-beam parameter		0.004		0.0001
Disruption parameter	36		6	
Polarization, %	80	70	90	None
Luminosity, $10^{33}\text{cm}^{-2}\text{s}^{-1}$	3.3		1.3	

Technological challenges

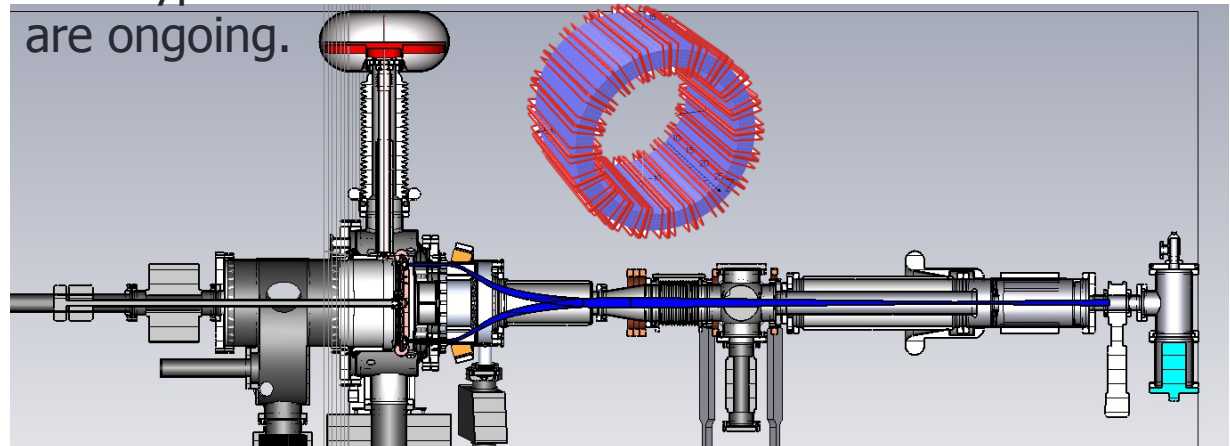
- High intensity (6 – 50 mA) polarized electron source
- High power ERL with multiple recirculations (high current SRF cavities, machine protection, MBBU, ...)
- Strong cooling of hadron beams (*eRHIC*)
- Low hadron β^* interaction region
- Crab-crossing (*eRHIC*)
- Beam-beam effects
- Techniques for intense e^+ beam (*LHeC*)



Polarized e-source: BNL Gatling Gun

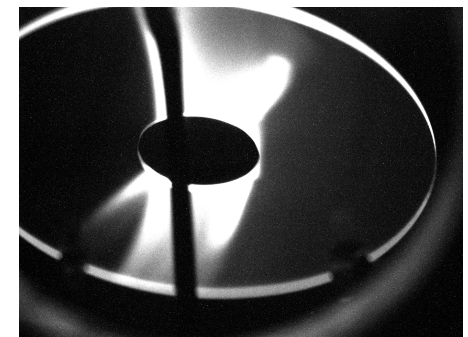
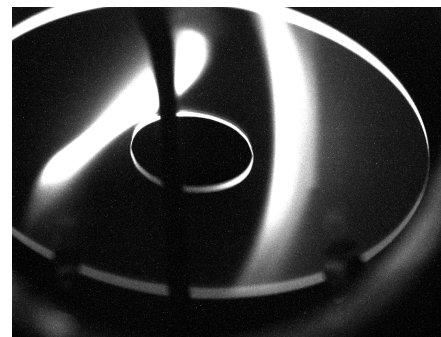
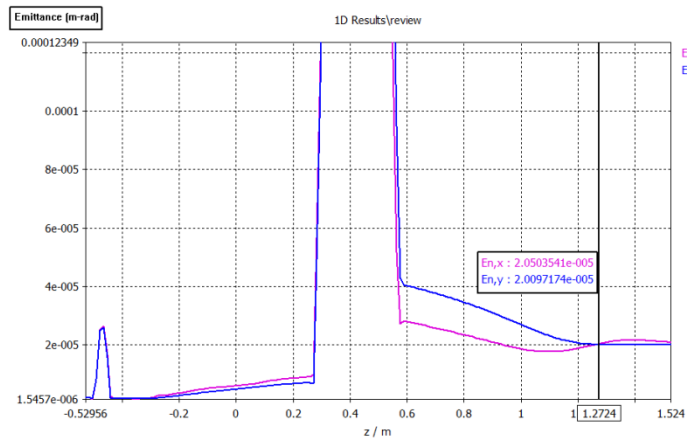


Prototype has been built. Initial tests with 2 cathodes are ongoing.



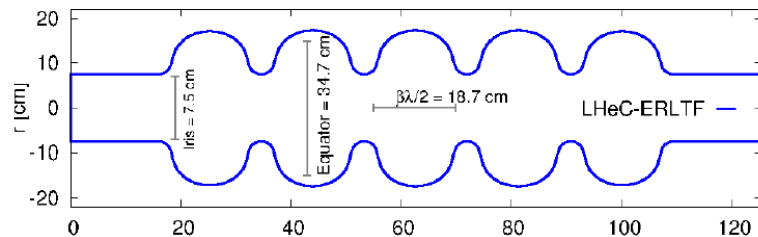
Ultimate goal: 2.5 mA/cathode, 50 mA total

First beam detected by the YAG screen.



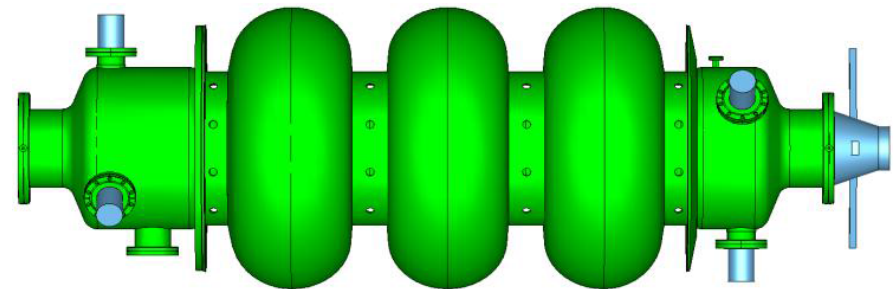
High current SRF cavities

LHeC: 802 MHz cavity and cryomodule development.
CERN-JLab-Mainz Collaboration



Parameter	Value
n_{cell}	5
V_{acc}	18 MV
f_0	801.58 MHz
W	131 J
aperture \varnothing	75 mm
equator \varnothing	347 mm
R/Q	462 Ω
G	276 Ω
E_{peak}	41 MV/m
B_{peak}	86 mT
$P_{\text{diss}} _{2\text{K}}$	< 28 W

eRHIC: 422 MHz cavity
Designed prototype:



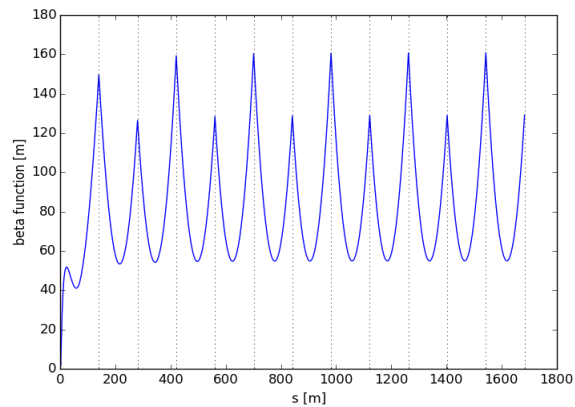
@W.Xu

Largest total beam current: 700 mA
(for 9.3 GeV top electron energy)

HOM power must be effectively damped:
LHeC: ~ 200 W
eRHIC: ~ 8 kW (in worst case)

Multipass Beam Break-Up

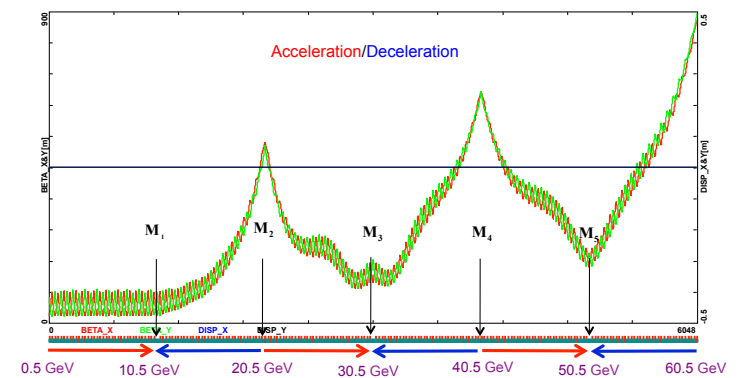
eRHIC



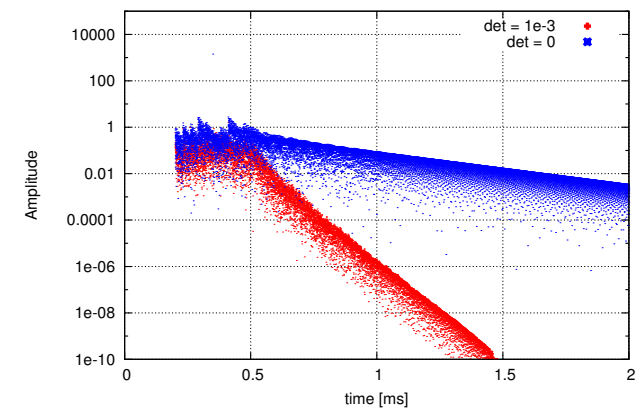
Multipass beam-breakup thresholds
for 16 pass operation (simulation results)

$\Delta f/f$ (rms)	Current Threshold (mA)
0	53
$5e-4$	95
$1e-3$	137
$3e-2$	225
$1e-2$	329

LHeC

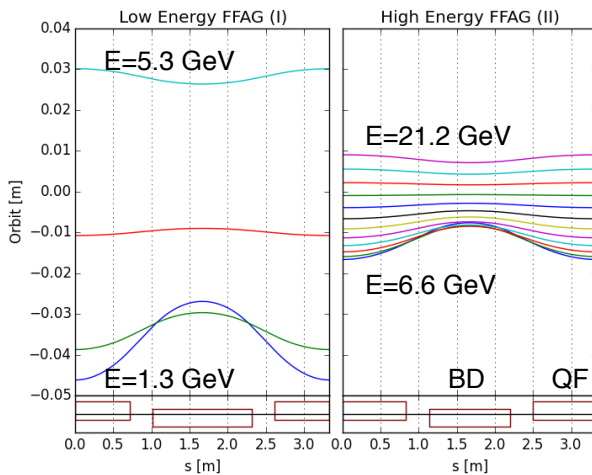


Detuning

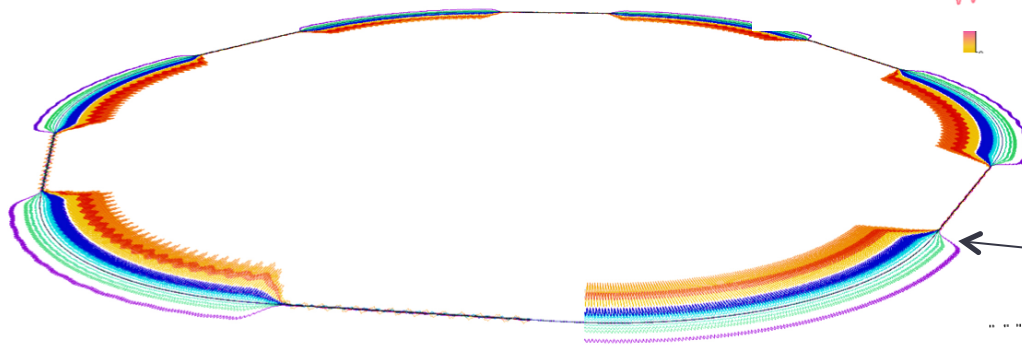


FFAG recirculation passes

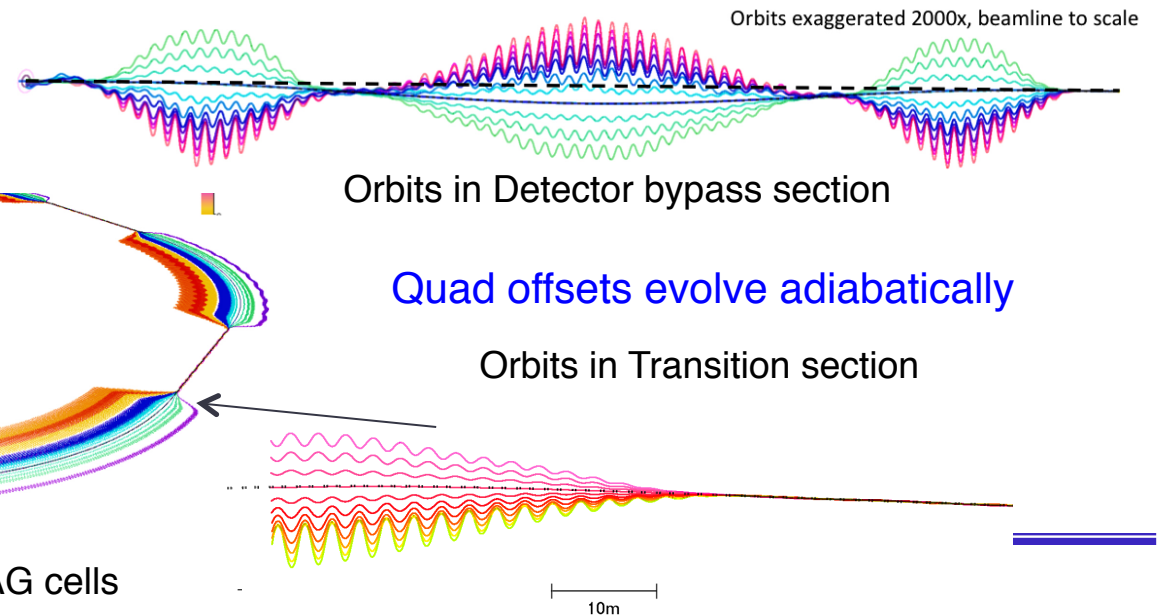
- eRHIC uses two FFAG beamlines to do multiple recirculations.
(FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



@S.Brooks, D.Trbojevic



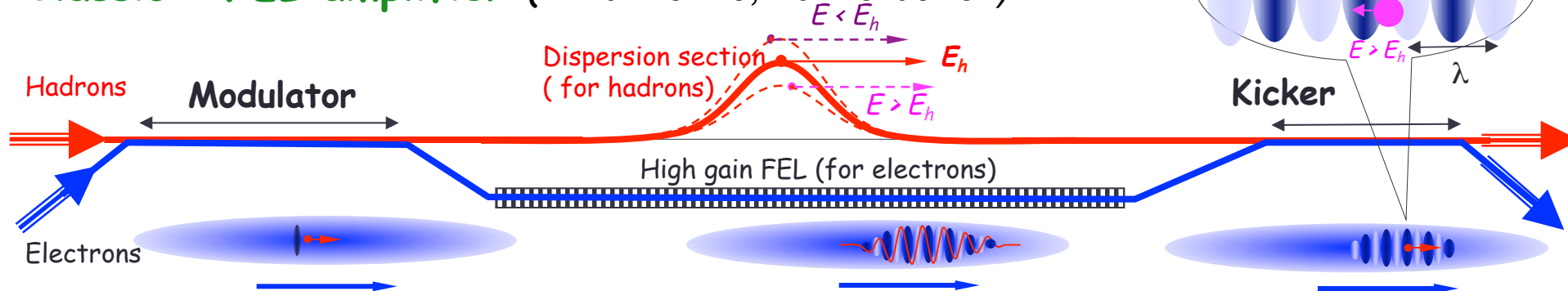
Each of two eRHIC FFAGs contain 1066 FFAG cells



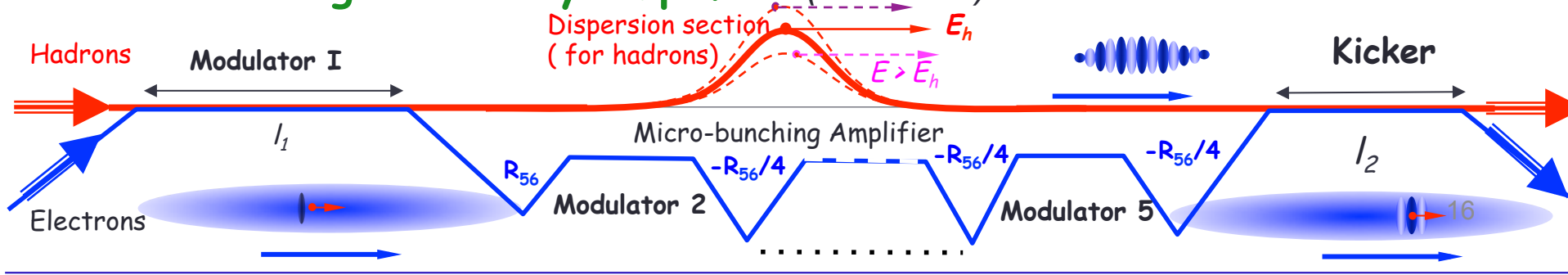
Advanced Cooling for eRHIC ion beam

High energy, high density ion beam need cooling with high band-width. **Coherent electron cooling: 10^{13} - 10^{17} Hz**
PoP CeC experiment in 2016-2017 RHIC runs.

Classic - FEL amplifier (V.Litvinenko, Ya.Derbenev)

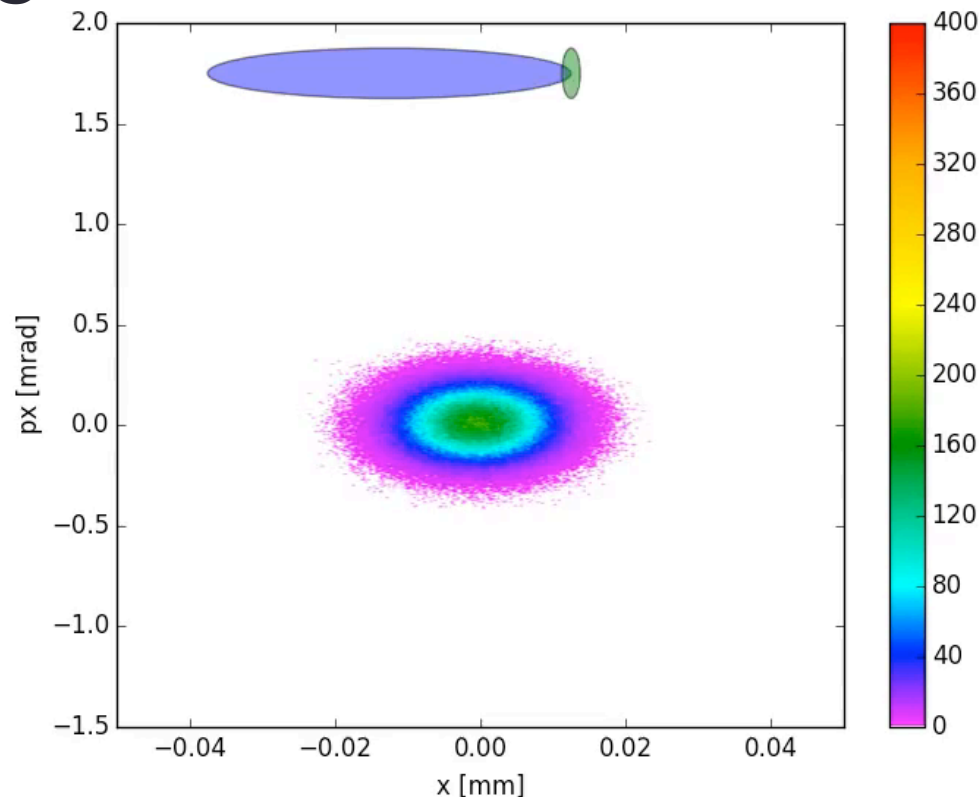


Micro-bunching instability amplifier (D.Ratner)



Beam-Beam Effect in Linac-Ring Scheme

@Y.Hao



Since using ERL:

Beam quality must be acceptable for deceleration.

Halo formation by due to electron beam disruption by the beam-beam interaction should be moderate.

Other specific beam-beam effects of linac-ring scheme:

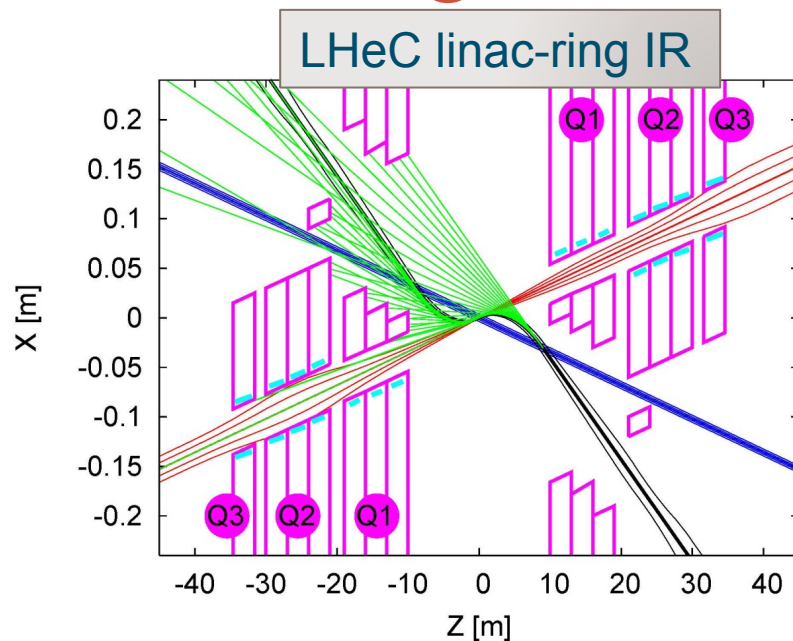
- Kink instability of hadron beam
- Heating of protons by electron parameter (orbit offset, intensity, emittance) fluctuations.

The effects are being studied by simulations and experimentally.

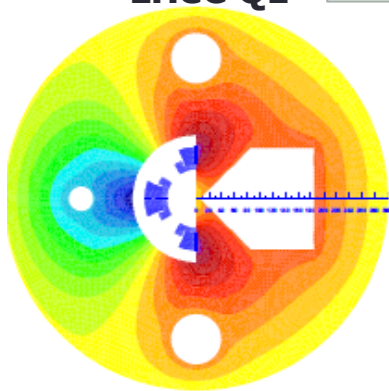
IR design

Using HERA and B-factories experience to resolve IR design issues:

- Strong beam focusing
- Fast separation (*avoiding parasitic beam-beam*)
- Managing synchrotron radiation fan (*absorbers, masks; precise orbit control; protection of SC magnets*)
- Detector integration (*Large acceptance; Large magnet apertures for propagation of the collision products*)
- Correction of chromatic effects

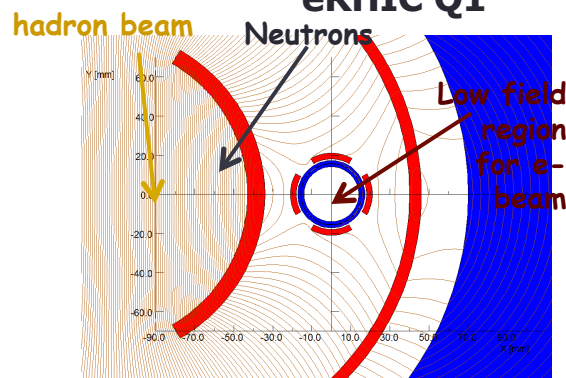


LHeC Q1

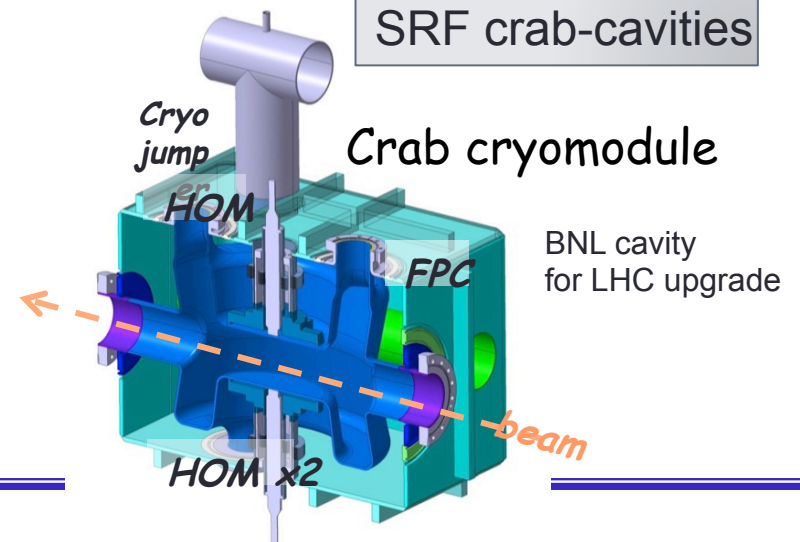


IR magnet designs

eRHIC Q1



SRF crab-cavities



ERL SCRF facility at CERN

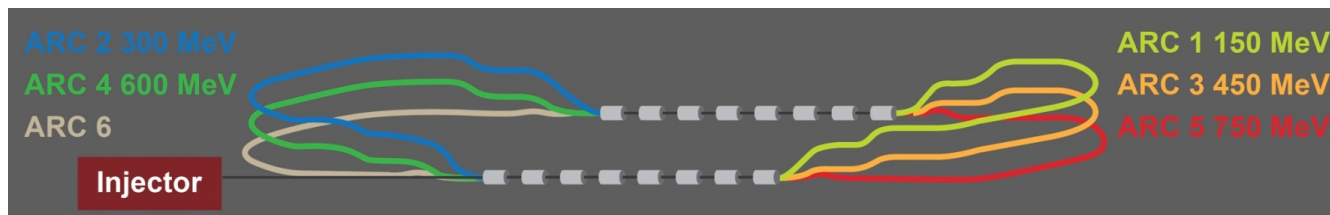
- Test facility for SCRF cavities and modules
- Test facility for multi-pass multiple cavity ERL
- Injector studies: DC gun or SRF gun
- Study reliability issues, operational issues
- Vacuum studies related to FCC
- Possible use for detector development, experiments and injector suggests ~1 GeV as final stage energy
- Test facility for controlled SC magnet quench tests
- Could it be foreseen as the injector to LHeC ERL and to FCC?

D. Pellegrini's Plenary talk

TARGET PARAMETER*	VALUE
Injection Energy [MeV]	5
Final Beam Energy [MeV]	900
Normalized emittance $\gamma\epsilon_{x,y}$ [μm]	50
Beam Current [mA]	10
Bunch Spacing [ns]	25 (50)
Passes	3

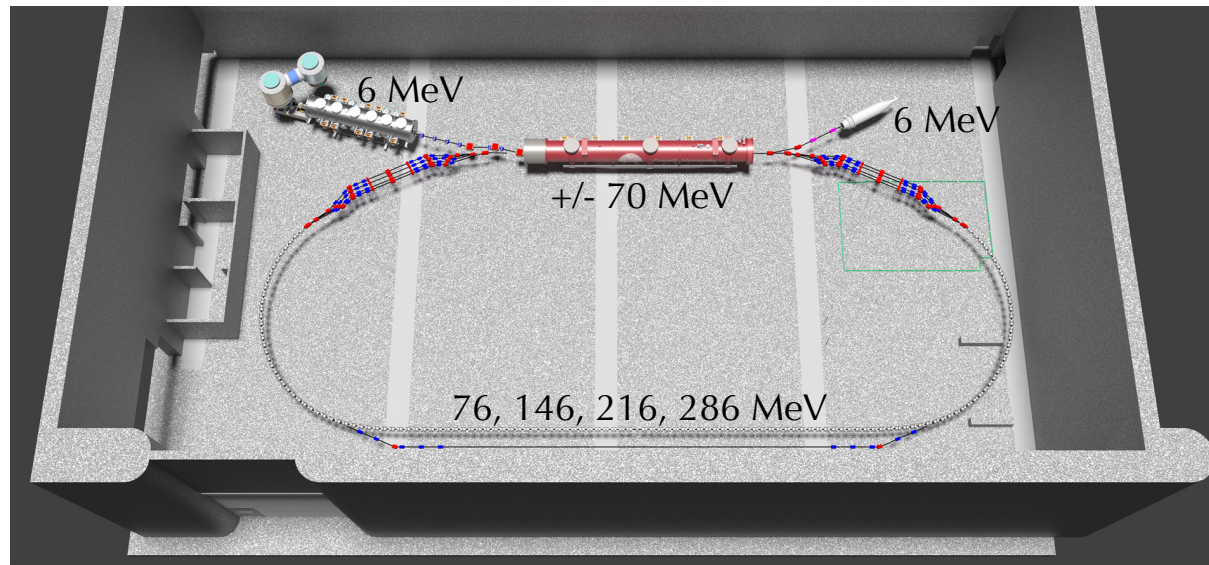
*in few stages

Conceptual Design
Study is underway



Cornell-BNL FFAG-ERL Test Facility (C β)

- NS-FFAG arcs, four passes (similar to first eRHIC loop)
- Momentum aperture of x4, as for eRHIC
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac
- Prototyping of essential components of eRHIC design

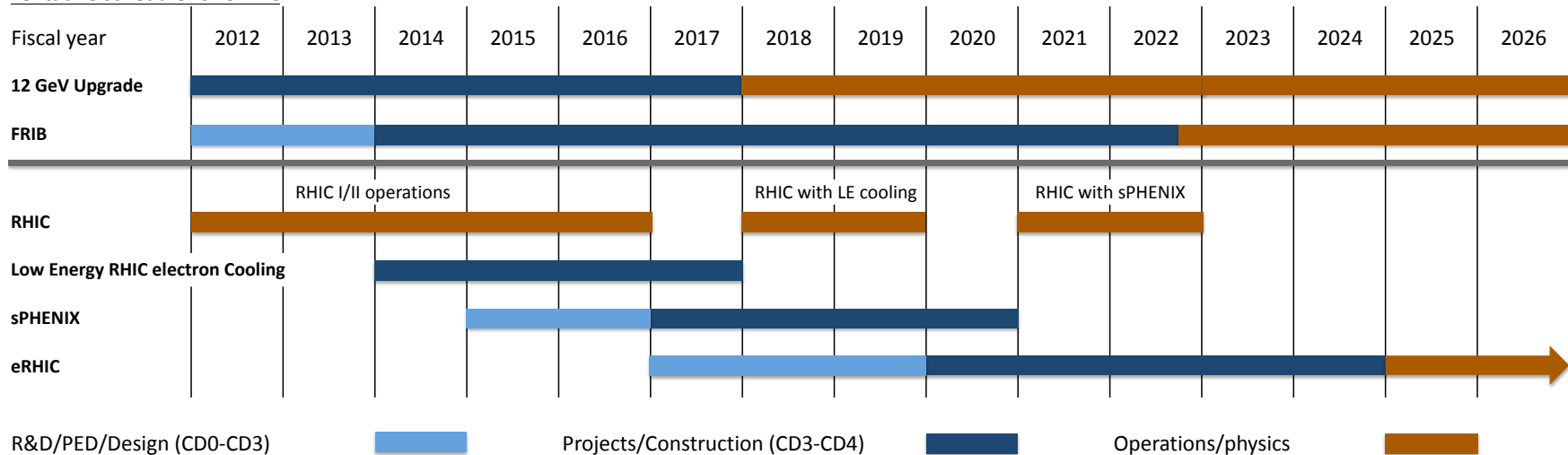


G.Hoffstaetter's Plenary talk

Also, possible ERL-related experiments for eRHIC are under consideration in JLab.
(Sattelite meeting, Thursday morning, Lecture Hall 1)

DOE NP Facilities and possible eRHIC schedule

Tentative schedule for eRHIC



Summary

- ERL technology provides a pathway for a high-luminosity electron-ion collider
 - ERL-based EIC designs have been developed in CERN (LHeC) and BNL (eRHIC)
 - Several R&D projects are underway to address the technological challenges for an ERL-based collider
 - ERL test facilities are planned in order to verify related technologies
-

eRHIC Luminosity

